PLATFORM: The GMV's Test-Bench for Formation Flying, RvD and Robotic Validation

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ABSTRACT

This paper describes the first steps for the setting up and exploitation of the PLATFORM test bench. PLATFORM test bench is intended for the ground testing and validation of GNC technologies and sensors for scenarios including synchronized flight of two or more spacecraft (Formation Flying and Rendez-vous and Docking) and it can be eventually extended to cope with the requirements for robotic applications (f.i. cooperative robotic operations on the Mars surface). PLATFORM test bench includes the particularity, with respect to other ground test benches, of allowing the use of real sensor measurements (including most of the error sources present in a space scenario, as transmission delays) obtained through the recreation of a real dynamic profile of spacecraft mock-ups by using an accurate numerically controlled robotic arm. This project has been supported by the Spanish National Space Program.

1.0 INTRODUCTION

In the last few years a clear tendency toward distributing the functionality of a single spacecraft among several satellites flying in formation has been shown, the most of the missions planning this kind of approach being characterized by very severe requirements in terms of relative positioning accuracy among involved platforms.

Formation flying could be defined as the coordinated motion control of a group of vehicles where the vehicle positions relative to each other are important. In general, the concept of navigation in formation can be applied to any kind of vehicle, like trucks, aircraft, mobile robots, etc.

Many future space applications will benefit from using this formation flying technology to perform distributed observations, including: Earth mapping (simultaneous interferometric SAR, magnetosphere), astrophysics (stellar interferometry), and surveillance.

The goal is to accomplish these science tasks using a distributed array of much simpler, but highly coordinated, vehicles. This approach represents a new systems architecture that provides many performance and operations advantages, such as:

- Enables extensive co-observing programs to be conducted autonomously without using extensive ground support.
- Increased separation between instruments could provide orders of magnitude improvement in space-based interferometry.
- An array of simpler micro-satellites provides a flexible architecture that offers a high degree of redundancy and reconfigurability in the event of a single failure.

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- Places the design emphasis on building and flying the science instruments, not on the development of the bus platform itself.
- Enables the low-cost, short lead-time instruments to be built, launched and operated at short time.

The strong interest in the formation flying concept shown by all space agencies is demonstrated by the number of missions that are being promoted. Some examples are (the first three are being promoted by the USA, while the last three correspond to European efforts):

- New Millenium Interferometer (NASA)
- Earth Observation-1 Mission (NASA)
- Orion (USA)
- FF Demonstration Mission, most likely to be hosted by SMART-3 (ESA)
- IRSI-Darwin (Infra-Red Space Interferometer) (ESA)
- LISA (Laser Interferometer Space Antenna) (ESA)

Due to the strong interest in the present and the coming future on this kind of missions, it is fundamental to develop low-cost and high-flexible test benches allowing the on-ground validation of as much of the involved technology as possible, in order to reduce the number of new technology chain elements to be tested and validated only through the costly space demonstration missions, which have the risk of suffering a failure in an intermediate element that makes impossible to test and validate the full technology chain and global functionality.

PLATFORM test bench tries to fill part of the gap existent between the currently ground facilities and the space demonstration flights, allowing higher reliable demonstration flights by reducing the testing and validation uncertainty through the ground checking in reproduced space conditions.

2.0 JUSTIFICATION OF PLATFORM TEST BENCH

From the operational point-of-view, the most stringent challenges imposed by formation flying are:

- Onboard sensing and inter vehicle communication required to perform the autonomous closed-loop relative navigation and attitude determination and control.
- High-level mission management to enable task allocation across the fleet of spacecraftt.
- High-level fault detection recovery to enhance the mission robustness.

The first point is of capital importance for the mission success, including the adequate gathering of scientific data. It is directly related with the other two points from the point of view of autonomy in control and operation of each satellite during the mission. The third point also includes the ability to detect potential collisions between vehicles and to conduct the corresponding avoiding maneuvers.

Most usual current ground testing test benches are based on SW simulators, distinguishing:

- Complete SW simulators (f.i. based on Matlab/Simulink), with dedicated functions to the simulation of the DKE and the simulation of the sensors measurements and actuators behaviour and, separately, dedicated blocks to the on-board functions: GNC, FDIR, Mission and Vehicle Management, Communications, …
- Complete SW simulators embedded in an environment allowing the use of real hardware in the loop (as f.i. the European environment EuroSim), where the use of an on-board processor ERC32 emulator allows to host all the on-board functions in a realistic space processor separated from the

DKE, sensors and actuators through a communication layer that reproduces the real interfaces. Real sensors may also be used, although the input of the sensors shall be conveniently simulated.

PLATFORM test-bench represents a step ahead, since it allows to generate a real relative DKE between the spacecraft constellation though the use of the robotic arm together with the use of real sensors where the provided measurements are based upon real signal transmission and/or real observations (GPS-like receivers/emitters, optical cameras or others). Actuators behaviour can be reproduced through the answer of the robotic arm to control commands produced by the on-board functions. This approach allows complementing the EuroSim-based test benches, since it reproduces the real dynamic of the constellation and provides real sensors measurements and keeping, at the same time, the advantage of using on-board processor emulators if desired (through the EuroSim environment) or using a PC-based on-board processor emulator as first step.

Fig. 1 presents the three concepts of test benches, showing the natural evolution from one to the others as consequence of the increasing validation and demonstration level before being ready for a demo flight.

Three main objectives are considered:

- The development of a hardware test-bed that actually mimics the relative motion of two or more satellites in different space scenarios.
- Implementation upon the test-bed of real navigation sensors, such as GPS receivers and pseudolites so as to test GNC algorithms under conditions as close as possible to real space conditions.
- Development and/or integration upon the test-bench of the most advanced guidance, navigation and control algorithms conceived to solve formation flying issues, such as those navigation algorithms developed by GMV for IRSI/DARWIN mission.

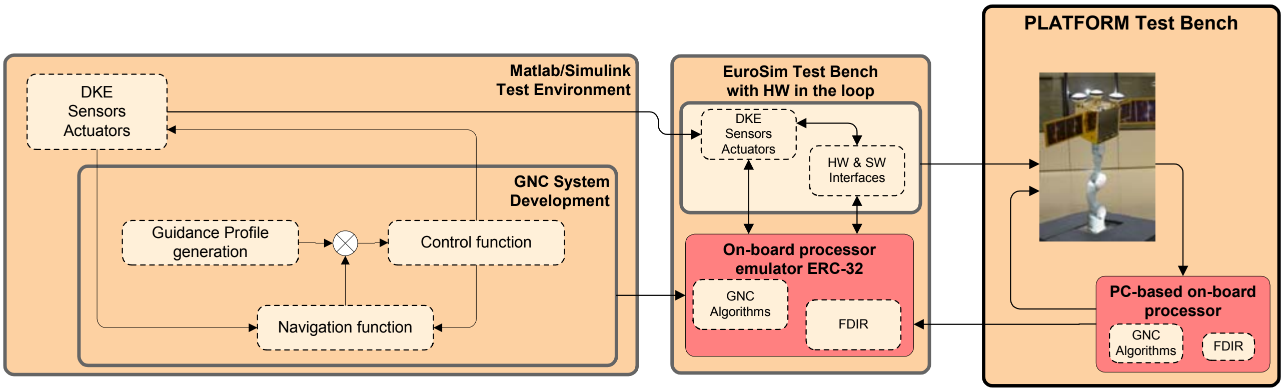

Fig. 1: From SW Simulators to PLATFORM

3.0 PLATFORM TEST BENCH SETTING

In order to reduce as much as possible the risk associated to fly multiple satellites in formation, which basically act, from the point of view of carried instruments, as a unique platform, it is worthwhile to test as much as possible on ground the required GNC algorithms, and sensors and actuators. This, together with the GMV involvement within the design and implementation of the navigation algorithms for different

ESA's FF mission (i.e. SMART-2/3, IRSI-DARWIN), brought to the idea of setting up the PLATFORM test-bench able to reproduce as much as possible on-ground space flying conditions, including sensors and actuators. The test bench will allow to investigate and test GNC, sensing, communication and mission management issues associated with precise formation flying.

PLATFORM, developed in the frame of the Spanish Space Programme, and co-funded by the Spanish Science Ministry (via CDTI) and GMV S.A. itself, has as major target to provide the more cost-effective solution for:

- On-ground Validating and Testing of Autonomous Navigation Algorithms for mini-satellites, FF, RvD and Robotic applications.
- Being the first step toward the validation of navigation sensors and actuators.

PLATFORM initial setting is specifically adapted to a DARWIN-type scenario (RF-based sensors are the main ones), although it is easily extensible to other scenarios. Current setting is composed by:

- A 6 DoF robotic arm for accurate reproduction of the constellation DKE.
- Two S/C mock-ups, that will host all the sensing equipments. They shall be representative in shape and structure of the real spacecraft, since the external structure will impact on the accuracy of the sensors measurements (multipath effect over GPS-like measurements, image processing in camera-based navigation).
- Four GPS-like pseudolites, for creating a virtual constellation of multiple spacecraft (only two mock-ups are used up to now).
- Two position-attitude GNSS receivers each with 3 antennas, for providing the navigation filters with measurements of relative position, velocity, attitude and attitude rate.
- One navigation camera, for acquiring relative navigation observations in case of scenarios with uncooperative spacecraft.
- One GPS constellation signal outdoor-indoor repeater.
- Several PCs, for controlling the robotic arm, the GPS-like pseudolites, hosting the on-board processor functions and others.

and provides the following major features:

- DKE computer-based generation.
- High level of DKE accuracy knowledge through numerically controlled robotic arm.
- Real sensing (radiated RF signals).
- Real on-board relative navigation algorithms (DARWIN-based as starting point).
- Very accurate performance assessment thanks to the accurately known robotic DKE.
- Possibility of feeding-back the robotic DKE with a control law.

One of the S/C mock-up is statically placed, while the second mock-up is placed on the robotic arm, simulating the formation flying S/C with respect to the first static one. The motion of the robot is given from one side by the DKE including all acting perturbation, and from the other by the S/C AOCS tending to fulfill the formation accuracy requirements. Fig. 2 shows a diagram of the test bench setting, and the following sections will introduce in detail the main components of PLATFORM.

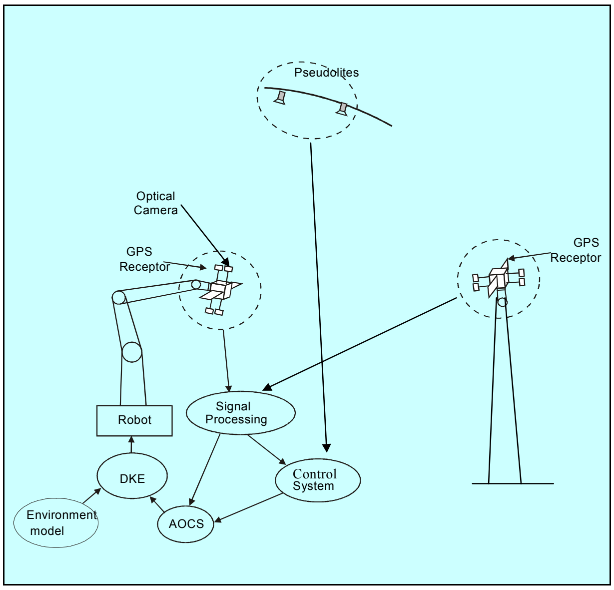

Fig. 2: PLATFORM test bench setting diagram

3.1 Robotic Arm for DKE Generation

The PA10-6CE Robot is a 6 degrees of freedom manipulator with the following characteristics: the arm unit weight is 38Kg and can lift an article of 10 kg weight. Six joints compose the vertical joint type architecture of the main body: S1, S2, E1, E2, W1, W2 from robot mounting base ("S" stands for shoulder joint, "E" for elbow joint and "W" for wrist joint). The robot arm has the reach of 1m, a positional repeatability of ±0.1 mm and is controlled by a personal computer. The following table shows joint operating limitations:

Name of axes	Limit (degree)			Maximum operating speed (rad/sec)
	Mechanical limit	Servo limit	Software limit	
S1 (Rotation)	±180	±178	±177	±1
S2 (Swing)	+127,-67	+125-65	+124,-64	±1
E1 (Swing)	+164,-113	+159,-108	+158,-107	±2
E2 (Rotation)	±270	±256	±255	±2 π
W1 (Swing)	±180	±166	±165	±2π
W2 (Rotation)	±270	±256	±255	±2π

Table 1: Joint operation range and speed limits

3.2 Spacecraft Mock-ups

Spacecraft mock-ups have been manufactured using an external structure on Aluminium alloy and recovered with a thermal coat. The following figure shows the mock-up in an intermediate assembly step. Characteristic size of the central body is 40 cm and the wingspan of 1.5 meters.

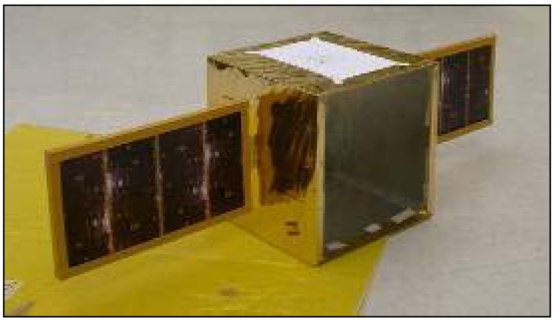

Fig. 3: Manufactured spacecraft mock-up

3.3 RF Signal Generation through Pseudolites

The GPS-like signal is generated by using the NAVindoor system manufactured by Space Systems Finland, and it is composed by five principal components:

- 4 Pseudolites (PL)
- 5 Radio modems
- 4 Helix antenna
- 1 Reference receiver (with patch antenna)
- 1 Master control unit

The system is designed to be used in a hall with floor size of approximately 100x100m and a height of 7m. The path loss when placed in the middle of one of the walls at 7m height, with a tilt angle of 20 degrees is hereafter shown.

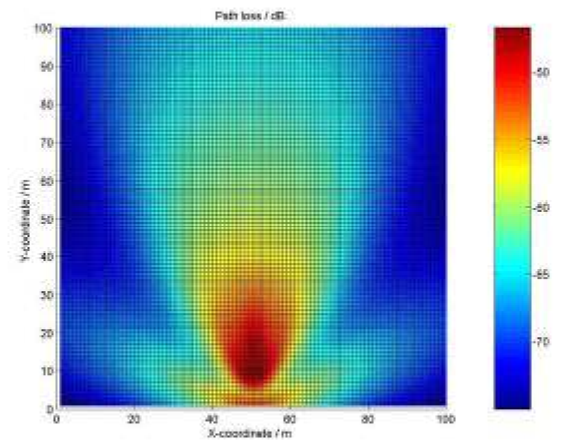

Fig. 4: Helix antenna path loss

3.4 Navigation Sensors

3.4.1 GPS Receivers

The selected GPS receiver is the PolaRx2 by Septentrio. PolaRx2 is a versatile high-end dual-frequency GNSS receiver for precise positioning and timing applications. It is a general-purpose 48-channel GNSS receiver for high-end OEM applications, capable of tracking satellites from up to 3 different antennas. The PolaRx2 supports reception of the L1 and L2 signals from up to 16 GPS satellites and is ready to handle GLONASS and SBAS (such as EGNOS and WAAS) signals.

PolaRx2 performance is detailed below by the following characteristics:

Measurement accuracy (1 Hz measurement rate)	
C/A pseudo ranges	0.15 m
P1/P2 pseudo ranges	0.1 m
L1 carrier phase	0.2 mm
L2 carrier phase	0.4 mm
L1/L2 Doppler	2.5 mHz (0.5 mm/sec)

Table 2: PolaRx2 provided measurements accuracy

3.4.2 Camera

A commercial high resolution digital camera (Sony DFW-X700) has been selected for camera-based navigation development. The image processing algorithms will be internally developed by GMV.

3.5 Integrated Test Bench

The result after the test bench integration is shown in the following figures.

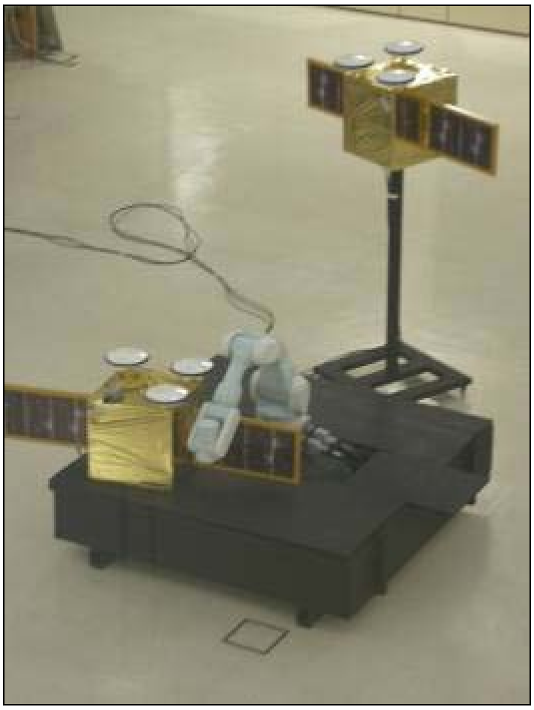

Fig. 5: Static mock-up close to the robotic arm

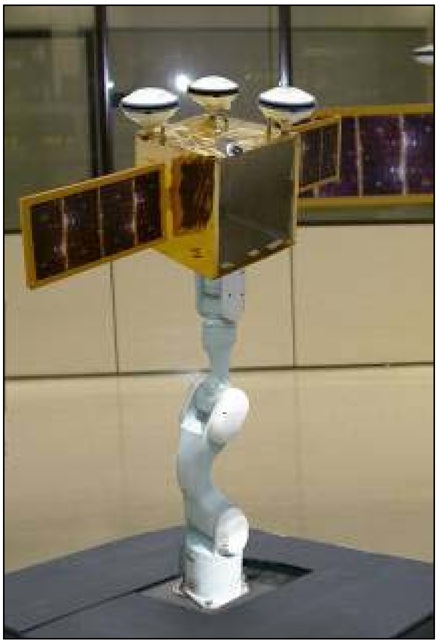

Fig. 6: S/C mock-up mounted at the top of the robotic arm

4.0 PLATFORM CALIBRATION

The correct and accurate calibration of the test bench is a key driver on the validation level that will be achieved by the test bench. Since the calibration residual error will be directly added over the performance figure evaluated for the GNC functions, it is fundamental to keep the test bench calibration residual as low as possible (target figure is the millimeter level).

For achieving this high level calibration, two sequential calibration steps are followed:

- Unitary calibration, where all equipments involved in the DKE generation and sensors measurements are calibrated with respect to its own references.
- Integrated test bench calibration, where all unitary references are referred to a common PLATFORM reference, that will be used as master reference.

4.1 Unitary Calibration

4.1.1 Robotic Arm

The robotic arm calibration procedure is split in two phases: the calibration error measurement and the compensation of this calibration error.

The purpose of the calibration operations is to reduce the gap existing between the robot simulation world and the real world. In fact, the robot controller works with a nominal model that, without the calibration, can be quite different from the real robot. To provide a link between simulation and the real world the calibration routines are performed both on the robot arm and on the possible tools and the work environment.

The pose term is commonly used to refer the position and orientation of an object. In three dimensions, the pose is given by the six-tuple [x, y, z, roll, pitch, yaw].

The robot calibration may be mainly performed in two ways:

- Pose error measurement: through the controller commands, the robot is requested to move to a particular position. External contactless measurement tools are used to measure the "true" pose. The difference between the measured and commanded location is the pose error.
- Pose matching: the robot is driven to a known location and the pose calculated by the robot controller is recorded. The difference between the known pose and that calculated by the controller leads to the pose error. The two poses are different because the controller uses the nominal robot model and measured joint angles at the encoders to calculate the pose, both different from the real robot world.

The first method is selected for calibration of the robotic arm, where the external contactless measurement tool selected is a laser theodolite (see Fig. 7).

Fig. 7: Calibration approach using a laser theodolite

From the calibration procedure, the system has an accurate model of the real robot with the work tools and the environment that can be used to make a robot compensation to improve its accuracy. The strategy compensation readapts the nominal points where the robot have to go. The main points to the compensation are the following:

- At the beginning and since the robot controller still has only the nominal robot model, the inverse kinematics used by the controller to calculate the joint values required to reach the wished position will produce error on the real achieved position.
- To get the robot moving to the correct position, the accurate model measured in the calibration phase (e.g. theodolite measurements) is used to perform inverse kinematics calculation, providing the required joint values for the real robot.
- Using these joint values back into the nominal robot model and performing forward kinematics, a new compensated position is obtained. This new position used by the robot controller with a nominal model gives the required joint values and thus moves to the required position.

In effect, this method actualizes the difference between the real model and the nominal model to every position, before transferring the program to the robot controller (see Fig. 8).

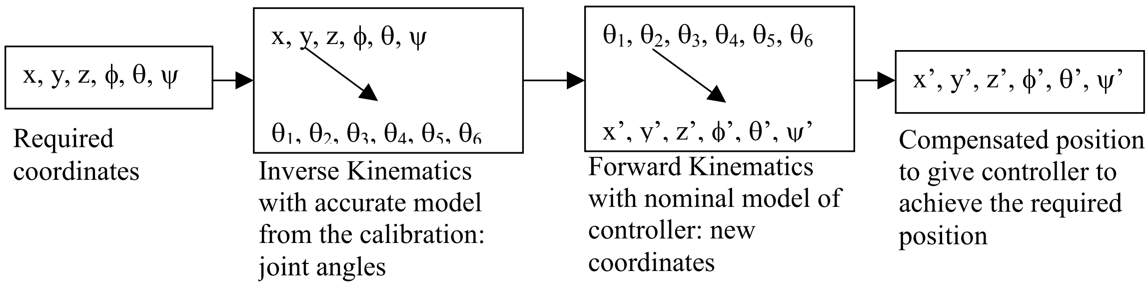

Fig. 8: False positions method

4.1.2 RF Pseudolites and GPS Receivers

The calibration of the GPS-like pseudolites and the receivers is made together in a common calibration process. The reason is that each of the equipments is necessary to calibrate the other one and, then, the collected measurements contain both pseudolites and receivers errors.

The main elements that are calibrated are:

- Center of phase of the pseudolites emitting antennas.
- Delay time between the GPS-like signal generation in the pseudolites and the antenna emission.
- Center of phase of the mock-up receiving antennas.
- Delay time between the GPS signal reception at the antenna and the insertion into the receiver processor.
- Multipath effects over the received signals at the mock-up antennas. Since the test bench is hosted indoor, and although the clear available environment (building room of 25x25x8 meters without any internal metallic structure) in terms of obstacles that could be the source of the multipath reflections and diffractions, the multipath effect is expected as one of the major error sources in the calibration process.
- Since the environment is frozen and will minimally change during testing campaigns, a multipath calibration campaign based on the repeatability of the multipath is currently being carried out.
- Desynchronisation between pseudolites clock and receivers clock. In this case, this parameter is part of the relative navigation state vector (as it would be in a real mission with multiple vehicles hosting RF emitting/receiving devices) and will be estimated through the relative navigation algorithms.

All above elements will be estimated and calibrated through the use of the measurements collected from the receiving antennas with the help of the laser theodolite tool that will allow to accurately measure the real position of the different equipment elements and compare against the collected sensors measurements. Different measurements combinations will be created to isolate some effects from the others.

4.1.3 Camera

The calibration of the camera is performed with the help of the laser theodolite measurement tool by matching the estimated position and attitude of the camera through the image processing with the real position and attitude measured by the theodolite.

4.2 Test Bench Calibration

After the unitary calibration of the different elements and equipment that compose the test bench, it follows to achieve the compatibility between all references through the use of a common reference. The common reference shall be provided, obviously, by an external measurement tool. In this case, the laser theodolite associated reference (or any third reference frozen with respect to the theodolite associated one) is our master (common) reference to which refer the rest of PLATFORM elements references) with respect to. The theodolite measurements of the PLATFORM elements will allow to determine the transformation matrices of any element reference frame to the master one.

Fig. 9 shows a schematic diagram illustrating the full test bench calibration approach.

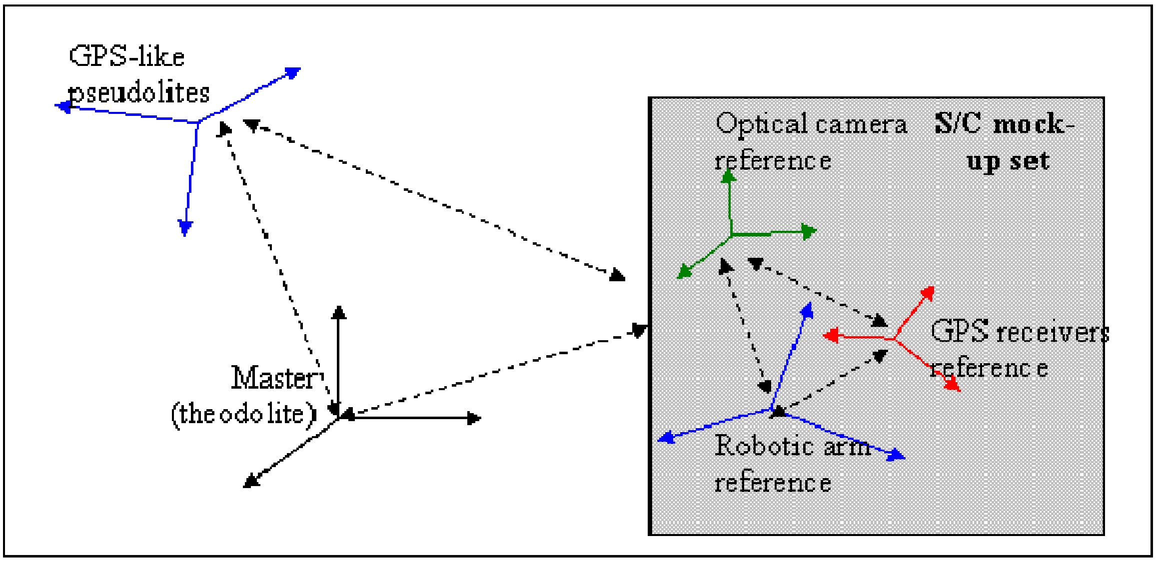

Fig. 9: Test bench elements calibration link

5.0 PLATFORM APPLICABILITY FIELD

PLATFORM composition and setting has been presented in the previous sections. From the test bench configuration and characterizations, it is possible to discuss the applicability fields and scenarios to which the test bench could be used for.

First of all, the direct application scenario (the one that has been kept in mind during the original proposal) is a short-range (1-25 meters) formation flying scenario composed by two or more platforms. Although only having a dynamically controlled robotic arm, our calibrated scenario offers the invaluable feature of being a repeatable scenario. This means that a multiple vehicle scenario could be generated by superposing several test bench configurations where different (in different tests that will be later superposed) vehicles are dynamically controlled by the robotic arm. Special care shall be taken into account on how the spurious effects are amplified by the superposition.

Secondly, medium and long-range formation flying scenarios may be recreated by using scalable scenarios. When using the optical camera for navigation purposes, the scalability shall be taken into account through the mock-up size, while when considering the GPS-like signal for navigation purposes, the scalability shall be achieved by imposing delays on the signal transmission from the pseudolites to the different S/C models.

In the same way, the medium and long-range phases of a RvD scenario (e.g. probe RvD with return vehicle in the Mars Sample Return scenario) may be achieved through scalable scenarios, while the short-range RvD phase (including the contact) is directly achieved by placing the static (target) spacecraft close to the dynamic controlled (chaser) spacecraft.

6.0 NEXT STEPS ON PLATFORM DEVELOPMENT

PLATFORM test bench is fully operative and it is under extension taking into account a dedicated ESA project targeting a complete Rendez-vous test bench.

Future extensions of PLATFORM test bench foresee:

- Cooperative robotic operations on a planetary surface exploration will require for a relative navigation system that can be based on the same concept as the formation flying, this is emitting/receiving RF devices coordinated by a reference device hosted on the landing platform. Adding real robotic prototypes to the test bench, the robotic arm may reproduce the landing sequence and platform aperture and the on-board robots may descend into a model of the planetary surface and test and validate the proposed autonomous navigation and robot fleet management algorithms.
- Landing scenario recreation through the modeling of the e.g. Mars surface. In this case, the robotic arm (with extended dynamic through the use of a track motion) will create the dynamic approximation to a surface model. Landing navigation based on optical camera observation may be tested in such scenario.

Finally, it shall be highlighted that, from all the capabilities offered by the presented multi-purpose, low-cost and flexible test bench, GMV is interested in exploiting its own expertise in the development, testing and validation of relative navigation algorithms. In other fields as guidance and control algorithms development and validation, sensing and/or actuators testing and validation, GMV is open to consider the collaboration with other interested companies. Utilization of PLATFORM test bench by other companies will have no cost other than the support people required to operate the test bench and will have no constraints other than calendar schedule.

7.0 CONCLUSIONS

Formation flying technology has recently attracted the attention of the space community as a very interesting way to conduct more efficient and robust missions, even with less cost. There are some important challenges to solve in the navigation and control areas in order to achieve successful missions.

To demonstrate the formation flying technology in space before intense ground testing is expensive and risky. Some way of ground simulation under close to real space conditions is needed. The proposed test bench tries to fill this gap in the path from concept to real mission demonstration.

The proposed test bench is at the same time flexible and reliable. Flexible because it allows to test different types of missions under different environment conditions, and reliable because it involves real hardware equipment under quasi-real physical configuration.

Finally, the test bench has been conceived to be able to increase its complexity and capabilities in the future with the inclusion of actuators, new sensors or more satellites.

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